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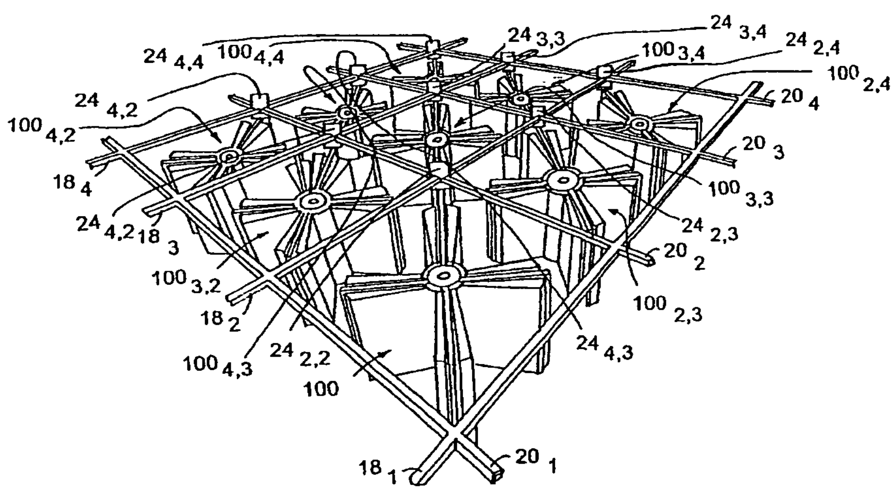

(57) Abstract: A microelectromechanical (MEMS) optical switch mechanism (100) includes a support structure, a rotary member rotatably mounted to the support structure, and a micromirror (24) coupled to the rotary member to be offset from the axis of rotation such that the micromirror is shifted from a first to a second position by rotation of the rotary member. The optical switch mechanism further includes a pair of electrodes for affecting rotation of the rotary member by an electrostatic force. The micromirror, rotary member, and electrodes are preferably formed from a single silicon substrate. The optical switch mechanism may be utilized in an optical cross-connect (OXC) device that includes a channel waveguide structure having a plurality of input waveguides (18) and a plurality of output waveguides (20) intersecting the input waveguides (18). The optical switch mechanisms exhibit switching times of less than 10 milliseconds while requiring less than 1 W per rotary member.

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MICROELECTROMECHANICAL OPTICAL SWITCH MECHANISM

Background of the Invention

1. Field of the Invention

The present invention generally relates to light optical circuits having an optical cross-connect device. More particularly, the present invention relates to microelectromechanical optical switch mechanisms for use in the optical cross-connect device of a light optical circuit.

2. Technical Background

Light optical circuits (LOCs) can serve several functions in a fiber optic network. One of the most important functions is that performed by LOCs having an optical cross-connect (OXC) device in which the signals from M input fibers are selectively routed to N output fibers. OXC devices can be realized using different design methodologies. The first utilizes free-space optical elements to direct collimated light from input fibers to output fibers. For small numbers of inputs and outputs, say M, N≤ 4, this method has the advantages of low insertion loss, low crosstalk, and low wavelength dependency. However, as M and N become larger, the divergence of the input beams in free space becomes problematical and must be compensated with additional optical elements. This establishes a physical size barrier for the integration of an OXC device based solely on free-space optics. Another key issue that must be addressed as M and N increases is the development of a cost-effective method for assembling and packaging all the elements that compose the OXC device. Clearly,

OXC designs based on discrete components, such as graded-refractive index (GRIN) lenses and hand-assembled switch actuators, are costly when compared to those based on integrated components using automated assembling methods.

Summary of the Invention

An aspect of the present invention is to provide an optical switching actuator that requires less power, may be made considerably smaller and compact, and that operates substantially faster than prior optical switch actuators.

In one aspect of the present invention, an optical device for directing a light signal is provided that comprises a rotary member movable about an axis of rotation an arcuate distance, and a micromirror coupled to the rotary member and offset from the axis of rotation. Movement of the rotary member through the arcuate distance moves the micromirror through an actuation distance. The actuation distance is greater than the arcuate distance.

In another aspect of the present invention, an optical device for directing a light signal is provided that comprises a waveguide structure including an input waveguide, an output waveguide intersecting the input waveguide to form a cross-point, and a trench formed in the cross-point. The optical device further comprises a MEMS structure connected to the waveguide structure. The MEMS structure includes a rotary member movable about an axis of rotation an arcuate distance, and a micromirror coupled to the rotary member and offset from the axis of rotation. Movement of the rotary member through the arcuate distance moves the micromirror through an actuation distance. The actuation distance is greater than the arcuate distance.

In another aspect of the present invention, an optical device for directing a light signal is provided that comprises an actuation device having a first portion and a second portion, the first portion being movable a first distance relative to a central axis. The optical device further comprises a micromirror connected to the second portion and offset from the central axis. The micromirror moves a second distance in response to the first portion moving the first distance, where the second distance is greater than the first distance.

In another aspect of the present invention, an optical device for directing a light signal is provided that comprises a micromirror, a micromechanical arm having a

first portion that is rotatable about an axis of rotation, a second portion connected to the micromirror and spaced therefrom by a plate member, and an actuator disposed adjacent to the plate member to apply a force to move the micromirror.

In another aspect of the present invention, an optical device for directing a light signal is provided that comprises a first light propagation path and a second light propagation path intersecting the first light propagation path to form a cross-point. The device further comprises a micromirror movable between a transmitting position and a reflecting position at the cross-point, and an actuator coupled to the micromirror. The actuator moves the micromirror between the transmitting position and the reflecting position in less than 10 μsec using less than approximately 200 mW of power.

In another aspect of the present invention, a method is provided for fabricating an optical device for directing a light signal. The method comprises the steps of: (a) providing a substrate; (b) forming a micromirror in the substrate; (c) forming a micromechanical arm having a first portion that is rotatable about an axis of rotation, and a second portion connected to the micromirror and separated therefrom by a plate member; and (d) forming an actuator disposed adjacent to the plate member to apply a force to move the micromirror.

Additional features and advantages of the invention will be set forth in the detailed description which follows and will be apparent to those skilled in the art from the description or recognized by practicing the invention as described in the description which follows together with the claims and appended drawings.

It is to be understood that the foregoing description is exemplary of the invention only and is intended to provide an overview for the understanding of the nature and character of the invention as it is defined by the claims. The accompanying drawings are included to provide a further understanding of the invention and are incorporated and constitute part of this specification. The drawings illustrate various features and embodiments of the invention, which, together with their description serve to explain the principals and operation of the invention.

Brief Description of the Drawings

In the drawings:

Fig. 1 is a top plan view of a waveguide structure used in an OXC device constructed in accordance with the present invention;

Fig. 2 is an oblique perspective view of the optical switch mechanism constructed in accordance with a first embodiment of the present invention;

Fig. 3A is a top plan view of the optical switch mechanism of the present invention when in a first position;

Fig. 3B is a top plan view of the optical switch mechanism of the present invention when in a second position;

Fig. 4 is a bottom plan view of an optical switching actuator matrix structure constructed in accordance with the present invention;

Fig. 5 is a schematic diagram illustrating the electrostatic interaction between a stationary electrode and the actuator arm of the optical switch mechanism of the present invention;

Fig. 6 is a graph illustrating the relation of the actuator arm angular position and actuator arm angular speed plotted as a function of time;

Fig. 7A is a bottom plan view of a silicon substrate following a first etching step;

Fig. 7B is a cross-sectional view of the substrate shown in Fig. 7A taken along line 7B-7B´;

Fig. 8A is a bottom plan view of a silicon substrate following deposition of a sacrificial layer and plugging of a hole in the sacrificial layer according to a second step of the inventive method;

Fig. 8B is a cross-sectional view of the substrate shown in Fig. 8A taken along line 8B-8B´;

Fig. 9A is a top plan view of the silicon substrate after etching in accordance with a third step of the inventive method;

Fig. 9B is a cross-sectional view of the substrate shown in Fig. 9A taken along line 9B-9B´;

Fig. 9C is a cross-sectional view of the substrate shown in Fig. 9A taken along line 9C-9C′;

Fig. 10A is a top plan view of the silicon substrate after etching in accordance with a fourth step of the inventive method;

Fig. 10B is a cross-sectional view of the substrate shown in Fig. 10A taken along line 10B-10B′;

Fig. 11A is a bottom plan view of the substrate after bonding to a glass substrate in accordance with a fifth step of the inventive method;

Fig. 11B is a cross-sectional view of the substrate shown in Fig. 11A taken along lines 11B-11B′;

Fig. 11C is a cross-sectional view of the substrate shown in Fig. 11A taken along line 11C-11C′;

Fig. 12A is a bottom plan view of the finished switch actuator structure as formed using the inventive method;

Fig. 12B is a cross-sectional view of the finished structure shown in Fig. 12A taken along line 12B-12B′;

Fig. 12C is a cross-sectional view of the finished structure shown in Fig. 12A taken along line 12C-12C′; and

Fig. 13 is a top plan view of an optical switch mechanism constructed in accordance with a second embodiment of the present invention.

Detailed Description of the Preferred Embodiment

Reference will now be made in detail to the present preferred embodiments of the invention, examples of which are illustrated in the accompanying drawings. Wherever possible, the same reference numerals will be used throughout the drawings to refer to the same or like parts.

Fig. 1 shows a waveguide structure 10 with which the optical switch mechanisms of the present invention may be utilized. The optical switch mechanisms are described below. As illustrated in Fig. 1, waveguide structure 10 includes a substrate 15 in which input waveguides 18_1-18_M are provided. Similarly, waveguide structure 10 includes output waveguides 20_1-20_N that are formed in substrate 15. In

general, output waveguides 20_1-20_N intersect input waveguides 18_1-18_M with each point of intersection corresponding to a switching cross-point where the light propagating through an input waveguide may be redirected to a selected output waveguide. The light propagating through an input waveguide may be selectively diverted to an output waveguide by means of a micromirror. To enable the selective diversion of light using micromirror 24, a trench 22 is formed at each cross-point where an input waveguide intersects an output waveguide. Trenches $22_{1,1}$-$22_{M,N}$ are typically formed at an angle to the input waveguides and may be filled with a refractive index matching oil that matches the index of refraction of the waveguide core material. As shown in Fig. 1, trenches $22_{1,1}$-$22_{M,N}$ preferably have a sufficient length to enable the associated micromirror $24_{1,1}$-$24_{M,N}$ to be moved, at one extreme, into a position that redirects all the light propagating through an input waveguide to one of the output waveguides (see mirror $24_{2,1}$, for example) and, at the other extreme, into a position where micromirror 24 is completely removed from the optical path of the associated input waveguide 18 so as to not redirect any of the light propagating through that input waveguide (see mirror $24_{1,1}$, for example). Thus, by moving micromirrors $24_{1,1}$-$24_{M,N}$, one may select which output fiber 20_1-20_N the light propagating through a particular input waveguide 18_1-18_M will exit.

To enable rapid switching, micromirrors $24_{1,1}$-$24_{M,N}$ are moved by means of optical switching mechanisms that respond to electrical signals provided from an electrical control circuit (not shown). As described further below, the inventive optical switching mechanisms of the present invention move the micromirrors 24 through rotary motion in response to an electrostatic force created when a voltage is applied to the electrodes of the mechanism.

Fig. 2 shows an optical switch mechanism 100 constructed in accordance with a first embodiment of the present invention. Mechanism 100 is a microelectromechanical system (MEMS) optical switch structure and includes an actuation device in the form of a rotary member 110 having a central cylindrical section 112 (also referred to as a first portion of rotary member 110) from which a plurality of micromechanical actuator arms 114a-114d extends radially outwardly. Actuator arms 114a-114d have the general appearance of a plurality of outwardly extending vertical plate members. The plate members have an area defined by their length and height, which are much greater than

their thickness. Actuator arms 114 may be of any suitable size, but there is shown by way of example actuator arms having a thickness of approximately 10 µm, a length of 110-180 µm, and a height of 150 µm. An examplary central cylindrical section 112 has an outer radius of approximately 20 µm and is slightly taller than actuator arms 114. Thus, by way of example, rotary member 110 has a total length of about 330 µm or less. One of ordinary skill in the art will recognize that the dimensions given above are dependent on a variety of factors, such as the pitch or spacing of cross-points in the waveguide.

A micromirror 24 is preferably coupled to rotary member 110 and is offset from the axis of rotation of rotary member 110. More specifically, micromirror 24 is attached to a second portion of rotary member 110, which forms part of first actuator arm 114a. The second portion of rotary member 110 is spaced from the first portion by the plate member portion of first actuator arm 114a. Micromirror 24 may be of any suitable size and has proportional dimensions of, for example, 2 µm thick, 30 µm wide, and 60 µm tall. These dimensions may vary depending upon a number of factors such as pitch or spacing of crosspoints in the waveguide. As will be discussed further below, micromirror 24 is preferably an integrally formed extension of first actuator arm 114a. Because 2 µm thick silicon is partially transparent to 1.5 µm light, an infrared reflecting metal, such as gold, is preferably coated on the side walls of micromirror 24.

As will be apparent to those skilled in the art, only first actuator arm 114a, to which micromirror 24 is attached, is needed to affect movement of micromirror 24. The remaining secondary actuator arms 114b-114d are provided so as to enable additional electrostatic force to be applied to rotary member 110. Although three secondary arms 114b-114d are shown, the number of such secondary actuator arms may vary from none to five or more. Because the distance of displacement of the ends of secondary actuator arms 114b-114d is not critical, secondary actuator arms 114b-114d need not be as long as first actuator arm 114a. For example, arm 114a may have a length of 180 µm while arms 114b-114d may have a length of 110 µm. Because micromirror 24 is offset from the axis of rotation of rotary member 110, a movement of rotary member 110 through an arcuate first distance causes micromirror 24 to move through a second actuation distance where the second distance is greater than the

arcuate first distance. By extending the length of first actuator arm 114a, which serves as a lever arm, the displacement of micromirror 24 may be increased for a given amount of rotation. See, for example, Figs. 3A and 3B, which show rotary member 110 rotated through its two most extreme positions.

Rotation of rotary member 110 is enabled by providing a central aperture 115 through cylinder 112 and by inserting a stationary pivot shaft 118 through central aperture 115 (see Fig. 12A). The central aperture 115 may have a radius of, for example, 5 μm while the radius of pivot shaft 118 may be slightly smaller so as to allow rotary member 110 to freely rotate about a central axis of pivot shaft 118. As shown in Fig. 12A, pivot shaft 118 has an enlarged head 156 that prevents rotary member 110 from sliding off of pivot shaft 118.

Mechanism 100 further includes a plurality of mechanical stops 120a-120d that are provided between actuator arms 114a-114d. As best illustrated in Figs. 3A and 3B, mechanical stops 120a-120d limit the angular rotation of rotary member 110 through a predetermined angle. This angle is sufficient to allow micromirror 24 to move the distance required to move into and out of the optical path of an input waveguide 18 of a waveguide structure 10. Because the predetermined angular rotation of rotary member 110 is selected to provide sufficient displacement of micromirror 24, the rotation angle is a function of the length of the actuator arm 114a. Criteria for selecting these parameters are discussed below.

Switch mechanism 100 also includes an actuator having a pair of electrodes 122a-122d and 124a-124d, respectively, provided on opposite sides of the plate members of each actuator arm 114a-114d. The electrodes have side wall dimensions that are comparable to the side wall (*i.e.*, plate member) dimensions of the actuator arms. As illustrated in Figs. 2, 3A, and 3B, a first electrode 122a-122d of each electrode pair is positioned on a side of the corresponding actuator arm 114a-114d that would contact the corresponding electrode 122a-122d when rotated counterclockwise while the second electrode 124b of each electrode pair is provided on an opposite side of the associated actuator arm. To affect rotation of rotary member 110, and hence displacement of micromirror 24, rotary member 110 is electrically grounded via pivot shaft 118, and a voltage potential difference is applied across each pair of electrodes. In this manner, the actuator arms 114 are electrostatically attracted to the higher

potential electrode. Since rotary member 110 is constrained to rotary motion about pivot shaft 118, this electrostatic force generates torque about the shaft axis causing rotary member 110 to rotate. Thus, as illustrated in Fig. 3A, when a second electrode 124 of each electrode pair is grounded and a higher potential is applied to the other electrode 122 of each pair, actuator arms 114 are attracted toward first electrode 122 thereby rotating rotary member 110 counterclockwise in a direction shown by arrow A until the actuator arms 114 contact mechanical stops 120 as shown in Fig. 3A. Preferably, mechanical stops 120 are configured and positioned so as to prevent actuator arms 114 from physically contacting either electrode 122 or 124 of the associated electrode pairs, which may otherwise possibly cause fusing of the actuator arms to one of the electrodes. Preferably, actuator arms 114 are prevented from getting any closer than about 2 μm to the adjacent walls of the electrodes.

To change the position of micromirror 24, the potential difference applied to electrodes 122 and 124 of each electrode pair is reversed such that first electrode 122 is grounded while a higher potential is applied to second electrode 124. This causes the associated actuator arm 114 to be electrostatically attracted to second electrode 124 thereby causing rotary member 110 to rotate in the clockwise direction as shown by arrow B until the actuator arms 114 are physically stopped by the corresponding mechanical stop 120 to be in the position shown in Fig. 3B, for example. As described further below, the force applied by the actuator electrodes to the plate member of the actuator arms is proportional to the area of the plate member.

As shown in Fig. 4, a plurality of such optical switch mechanisms 100 is formed on a substrate in an array. This structure may then be flipped upside down and placed on a waveguide structure 10 such as that shown in Fig. 1, with the micromirrors 24 of each switch mechanism 100 positioned within a corresponding trench 22. The optical switch mechanisms 100 may then be independently controlled by an electrical control circuit to shift micromirrors 24 into and out of the optical paths of input waveguides 18.

In order to determine switch parameters, such as switching time and required switching voltage for the optical switch mechanism 100 described above, it is desirable to characterize all the forces that act on the body of an actuator arm 114 as it rotates about pivot shaft 118. These forces include the electrostatic forces between the plate members of actuator arms 114a-114d and the sides of the electrodes, the frictional

forces between the bottom of the central cylindrical portion 112 of rotary member 110 and the substrate that is used to retain rotary member 110 on the pivot shaft 118, and, since the entire device is assumed to be immersed in the index matching fluid, the viscous drag forces acting on the actuator body as it moves through the liquid.

The electrostatic force, F_e, that a differential area on the actuator arm plate member experiences depends on the angle, θ, which the actuator arm 114a makes with respect to the electrode face. Fig. 5 is a diagram illustrating the electrostatic interaction between stationary electrode 124a and actuator arm 114a that is free to rotate about the origin (Point A). The electrostatic interaction is assumed to be confined to the actuator arm region between $L1$ and $L2$. The magnitude of this force may be written as:

(1) $$F_e(\theta,x)=\frac{\varepsilon}{2}V^2\frac{dA}{\left[D_{gap}+x\sin(\theta)-\frac{W}{2}\cos(\theta)\right]^2}$$

where D_{gap} is the minimum distance from the center of actuator arm 114a to the surface of electrode 124a, V is the applied voltage, ε is the dielectric constant of the fluid, dA is the differential actuator arm area, W is the actuator arm width, and x is the distance along actuator arm 114a as measured from the pivot point (Point A in Fig. 5). Since actuator arm 114a is constrained to rotational motion by pivot shaft 118 (Fig. 2), this force induces a differential torque:

(2) $$d\tau(\theta,x)=x\cdot F_{\perp}=x\cdot F(\theta,x)\cos(\theta)$$

and, upon integrating along the actuator arm axis from $L1$ to $L2$, the total torque can be written as:

(3)

$$\tau(\theta,h,W,L1,L2)=\int_{L1}^{L2}d\tau(\theta,x)dx=\frac{\varepsilon hV^2\cos(\theta)}{2}\int_{L1}^{L2}\frac{x\,dx}{D_{gap}+x\sin(\theta)-\frac{W}{2}\cos(\theta)}$$

where h is the height of actuator arm 114a. Similar formulas can be found for the remaining three arms 114b-114d, resulting in an equation for the combined torque of the device:

$$(4) \qquad \tau_{total}(\theta) = N \cdot \tau(\theta, h_{act}, W_{act}, L1_{act}, L2_{act}) + \tau(\theta, h_{lever}, W_{lever}, L1_{lever}, L2_{lever}).$$

Here h_{act}, W_{act}, $L1_{act}$, and $L2_{act}$ denote the dimensions and initial and ending integration points of the three similar actuator arms 114b-114d, while h_{lever}, W_{lever}, $L1_{lever}$, and $L2_{lever}$ denote the dimensions and initial and ending integration points of the lever actuator arm 114a that holds micromirror 24. N represents the number of actuator arms.

Counteracting this generated torque are both frictional and viscous forces. Since the only point of contact between rotary member 110 and the substrate that retains the device on pivot shaft 118 is at the bottom of cylindrical portion 112 of rotary member 110, the frictional torque can be written as:

$$(5) \qquad \tau_{friction}(\theta) = \mu_{Si}\, \rho_{Si}\, Vol_{act}\, g\, \frac{R1 + R2}{2}$$

where μ_{si} is the coefficient of friction for silicon sliding on silicon, ρ_{si} is the mass density of silicon, Vol_{act} is the total volumé of the three actuator arms (114b-114d), the lever arm (114a) with mirror 24, and the central cylindrical portion 112 of rotary member 110, g is the gravitational acceleration constant, and $R1$ and $R2$ are the inner and outer cylinder radii.

The fluid damping forces are slightly more complicated, but assuming inertial forces are negligible compared to viscous forces (*i.e.*, low Reynolds number), the total damping force due to the presence of the fluid is:

$$(6) \qquad \tau_{fluid}(\omega) = \tau_{bulk}(\omega) + \tau_{ring}(\omega)$$

where ω is the angular speed of the rotary actuator and τ_{bulk} is the bulk viscous torque experienced by the radial arms of the actuator. τ_{ring} is the viscous torque experienced by the cylindrical portion 112 of rotary member 110 resulting from Couette flow of fluid in the regions between cylindrical portion 112 and shaft 118, between mechanical

stops 120 and cylindrical portion 112, and lastly between the top and bottom of cylindrical portion 112 and retaining substrate (see R. Dodge and M. Thompson, "Fluid Mechanics," New York: McGraw-Hill Book Company, Inc., p. 165, 1937).

Now that all the forces have been identified, an equation of motion for actuator arm 114a can be expressed as:

$$\ddot{\theta}(t)=\frac{\tau(\theta,\dot{\theta})}{I_{total}} \quad (7)$$

where the total moment of inertia, I_{total}, is the sum of four terms:

$$I_{total}=I_{mirror}+I_{lever\ arm}+I_{cylinder}+3I_{actuator\ arm} \quad (8)$$

Equation (7) can be solved numerically by considering differential time steps Δt, yielding:

$$\theta(t_i)=\theta(t_{i-1})-\omega(t_i)\Delta t \quad (9)$$

where

$$\omega(t_i)=\frac{\tau_{total}(\theta(t_{i-1}))-\tau_{friction}(\theta(t_{i-1}))-\tau_{fluid}(\omega(t_{i-1}))}{I_{total}}\Delta t \quad (10)$$

$$\theta(0)=\theta_0 \quad ; \quad \omega(0)=0$$

Here θ_0 is defined as the initial angle of actuator arm 114a with respect to electrode 124a. The initial angular speed, ω, at θ_0 is assumed to be zero.

EXAMPLE

The invention will be further clarified by the following example, which is intended to be exemplary of the invention. In this example, an optical switch mechanism is referenced and has the general appearance as switch mechanism 100 shown in Fig. 2. The dimensions of the exemplary optical switch mechanism are listed in Table 1 below.

Table 1

Parameter	Value
Voltage	20 V
Maximum Angle	12 °
Electrode/arm gap width	2 μm
Fluid dielectric constant	$1.9 \cdot 10^{-5}$ μF/m
Fluid Viscosity	0.19 stokes
Actuator Drag Coefficient	1
Mirror height	60 μm
Mirror length	30 μm
Mirror width	2 μm
Lever arm height	150 μm
Lever arm length	180 μm
Lever arm width	10 μm
Actuator arm height	150 μm
Actuator arm length	110 μm
Actuator arm width	10 μm
Cylinder inner radius	6 μm
Cylinder outer radius	20 μm
Cylinder height	150 μm
Pivot shaft radius	5 μm
Silicon mass density	2.3 g /cm^3
Silicon friction coefficient	1

Fig. 6 shows a plot of the actuator arm angle, θ, and angular speed, ω, as a function of time for an actuator device with the parameters listed in Table 1. From Fig. 6, the maximum angular velocity is approximately 0.16°/μs which translates into a maximum linear speed at the micromirror position (180 μm from pivot center) of ~50 cm/s. In terms of the Reynolds number which is defined as $R = \frac{Lv}{\eta}$ where L is a

characteristic length, v is the linear velocity of the object moving through the fluid, and η is the fluid viscosity, we obtain $R \sim 4.7$ for the actuator device under consideration. Since R is relatively low, this implies the assumption that the fluid inertial forces could be neglected compared to viscous forces was indeed valid.

Using standard micro-fabrication techniques, such as that described below, a novel electrostatic MEMS optical switch mechanism 100 has been fabricated. This switch is arrayed and integrated with a silica channel-waveguide substrate 10 to yield a compact OXC device (*e.g.*, a 64 x 64 OXC could be fabricated on a 2 cm x 2 cm silica substrate). Such a compact OXC device has its waveguides equally spaced by less than approximately 250 μm. For a device having a mirror submerged in oil, the device has a switching time of less than 500 μsec when 20 V is applied to the device. Switch times of under 200 μsec have been achieved by applying higher voltages. In a free space embodiment where oil is not disposed in a trench, switch times in the μsec range have been achieved. Because the electrostatic actuator of the present invention is based on voltage rather than current, it requires much less power to operate than thermal actuators. Thus, less than 1 W of power is needed to drive each actuator. In fact, as little as 0.2 W of power is needed to drive an actuator of the present invention.

As illustrated in Figs. 7A-12C and described below, optical switch mechanism 100 may be constructed entirely of silicon and may be manufactured using standard micro-fabrication techniques thereby minimizing assembling costs. To form the inventive optical switch mechanism, one first obtains a bulk <110> single crystal silicon substrate 150. Then, the first step is to anisotropically etch a portion of the bottom surface of the silicon substrate using potassium hydroxide (KOH) to etch away planes of the substrate that are not parallel with the <111> plane of the silicon substrate. Such an anisotropic etching technique is taught in "Micro-opto-mechanical Devices Fabricated by Anisotropic Etching of <110> Silicon," J. Micromech. Microeng. 5, 305 (1995) by Y. Uenshi et al. This is done to first create micromirror 24, which is left with an atomically smooth reflective first surface in the <111> plane as a result of the anisotropic etching. By forming micromirror 24 in this manner, it exhibits much lower insertion loss than other forms of micromirrors used in such devices. The resulting structure after this first etching step is illustrated in Figs. 7A and 7B. As

shown, the entire bottom surface, with the exception of a peripheral rim 152 of substrate 150 and micromirror 24, is etched away to a depth that is approximately 60 μm, which corresponds to the height of micromirror 24.

As the second step in this process, a sacrificial layer 154 is deposited in the etched-out areas of the structure shown in Figs. 7A and 7B using standard masking and depositing techniques. A small hole is formed in sacrificial layer 154 and a silicon plug 156 is filled into the hole and formed so as to have a head portion 158 that is larger in diameter than the hole. This structure will correspond to the head portion of pivot shaft 118. The resulting structure is shown in Figs. 8A and 8B.

The next step is to flip the structure over and to etch the opposite side of the silicon substrate using reactive ion etching (RIE). As shown in Figs. 9A-9C, this etching step is used to form most of rotary member 110 including actuator arms 114a-114d and central cylindrical portion 112. Also formed by this step are mechanical stops 120a-120d, a portion of pivot shaft 118, and electrodes 122a-122d and 124a-124d.

In the next step, KOH etching or deep reactive ion etching (DRIE) is used to form aperture 115 in cylindrical portion 112 thereby forming the requisite separation between pivot shaft 118 and cylindrical portion 112. As shown in Figs. 10A and 10B, this step is also used to create the separation between the ends of the actuator arms and side walls 152.

Next, the structure is again flipped over and bonded to a substrate 160 that may be made of either silicon or glass. As shown in Figs. 11A-11C, side walls 152, pivot shaft 118, mechanical stops 120, and electrodes 122 and 124 are bonded to substrate 160 while no portion of rotary member 110 is bonded to substrate 160.

In the final step, the sacrificial layer 154 is etched away thereby leaving the structure shown in Figs. 12A and 12B, which corresponds to the structure shown in Figs. 2, 3A, and 3B. As is apparent, rotary member 110 is free to rotate about pivot shaft 118. Also in the last step, the height of side walls 152 is reduced to enable the structure to be turned upside down and laid on an optical switch matrix structure such as that shown in Fig. 1 while at least a portion of micromirrors 24 may extend downward into a corresponding trench filled with a refractive index matching oil. Side

walls 152 may thus be used to support and bond the structure shown in Figs. 12A-12C to the structure shown in Fig. 1.

The wiring that applies the potential difference across the electrodes may be preformed on substrate 160 and then aligned with the respective electrodes when bonding substrate 160 onto the structure shown in Figs. 10A and 10B.

A second embodiment of a MEMS optical switch structure is shown in Fig. 13. As shown in Fig. 13, the optical switching structure of the second embodiment is nearly identical to that of the first embodiment with the exception that an additional micromirror 24b is attached to actuator arm 114c. Actuator arm 114c may have the same or different length than actuator arm 114a. By providing a second micromirror 24b on the switching mechanism, the two micromirrors may simultaneously be moved into different waveguide optical paths in an optical switching matrix. Alternatively, one mirror may be simultaneously moved into one path while the other mirror is moved out of another path depending upon the positioning of the switching mechanism relative to the cross-points of the optical paths. The switching mechanism may also include additional micromirrors positioned on various combinations of the actuator arms.

It will become apparent to those skilled in the art that various modifications to the preferred embodiment of the invention as described herein can be made without departing from the spirit or scope of the invention as defined by the appended claims.

The invention claimed is:

1. An optical device for directing a light signal, said optical device comprising:
an actuation device having a first portion and a second portion, said first portion being movable a first distance relative to a central axis; and
a micromirror connected to said second portion and offset from said central axis,
said micromirror moves a second distance in response to said first portion moving said first distance, wherein said second distance is greater than said first distance.

2. An optical device for directing a light signal, said optical device comprising:
a micromirror;
a micromechanical arm having a first portion that is rotatable about an axis of rotation, and a second portion connected to said micromirror and spaced therefrom by a plate member; and
an actuator disposed adjacent to said plate member to apply a force to move said micromirror.

3. The optical device of claim 2, wherein said actuator includes a pair of electrodes disposed on either side of the area of said plate member.

4. The optical device of claim 1 or 2, wherein said first portion includes a cylinder rotatable about a pivot shaft.

5. The optical device of claim 1 or 2, wherein said actuator applies an electrostatic force to said plate member to move said micromirror when a voltage of about 20 V or less is applied to said actuator.

6. The optical device of claim 1 or 2, wherein said actuator applies an electrostatic force to said plate member to move said micromirror when power of about 200 mW or less is supplied to said actuator.

7. The optical device of claim 1 or 2, wherein said actuator causes said micromirror to switch between a reflecting position and a non-reflecting position in about 500μsec or less.

8. The optical device of claim 1 or 2, wherein said actuator causes said micromirror to switch between a reflecting position and a non-reflecting position in about 10μsec or less.

9. The optical device of claim 1, wherein said actuation device is rotatably mounted to a support structure.

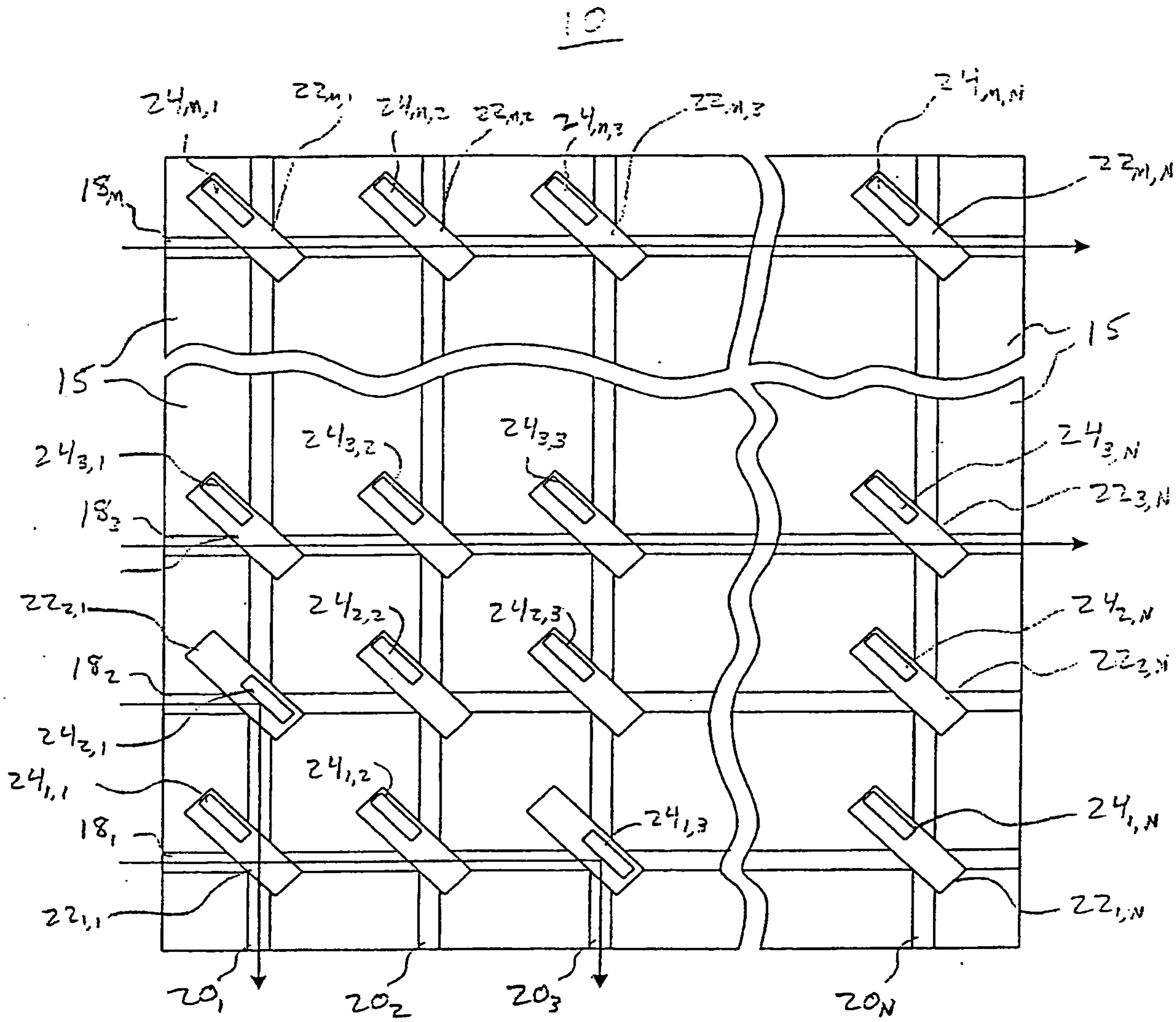

10
24m,1
22m,1
24m,2
22m,2
24m,3
22m,3
24m,N
22m,N
18m
15
15
24 3,1
24 3,2
24 3,3
24 3,N
22 3,N
18 3
22 2,1
24 2,2
24 2,3
24 2,N
22 2,N
18 2
24 2,1
24 1,1
24 1,2
24 1,3
24 1,N
18 1
22 1,1
22 1,N
20 1
20 2
20 3
20 N

FIG. 1

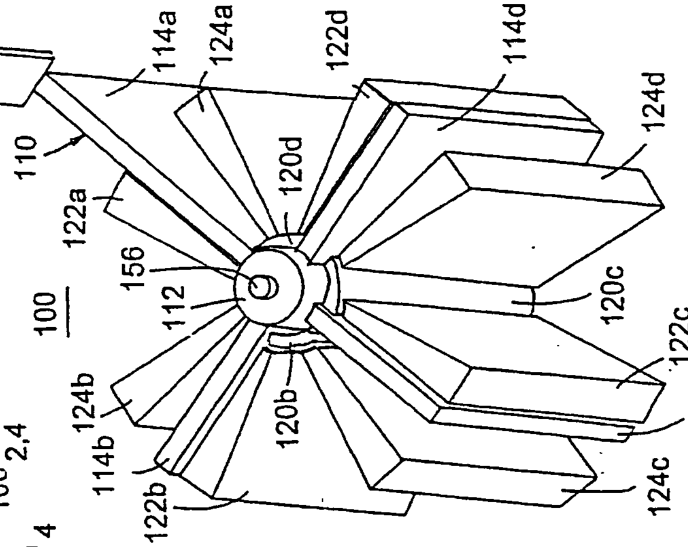


Fig. 2

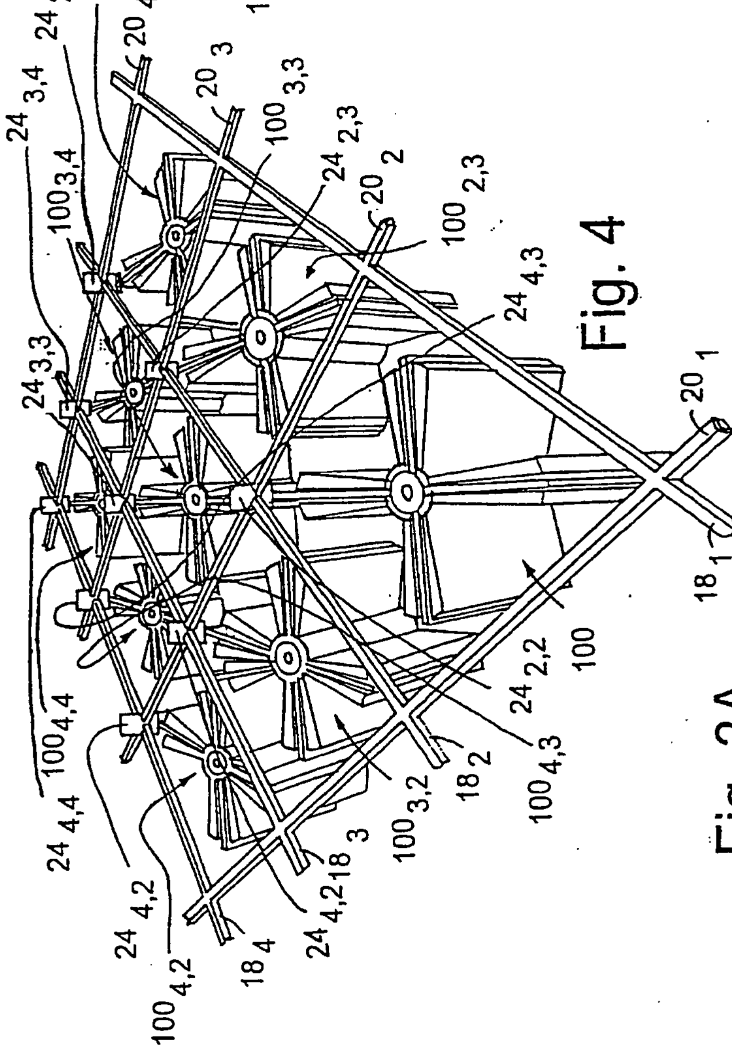


Fig. 4

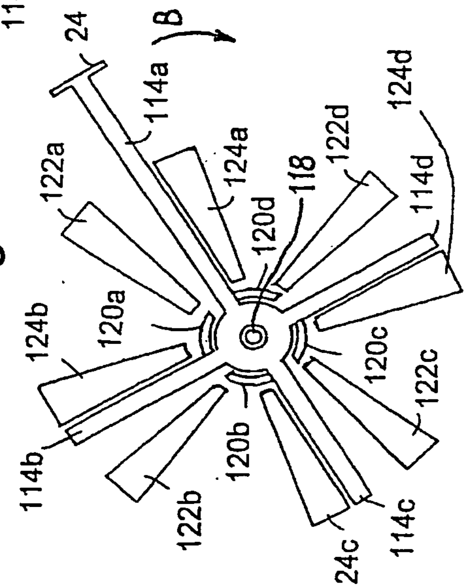


Fig. 3B

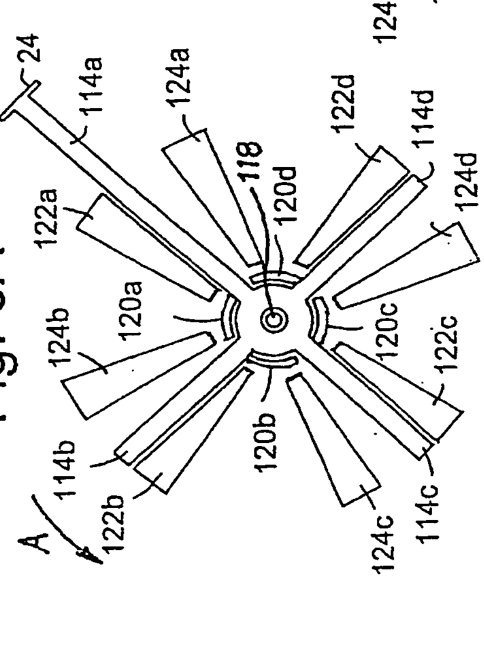


Fig. 3A

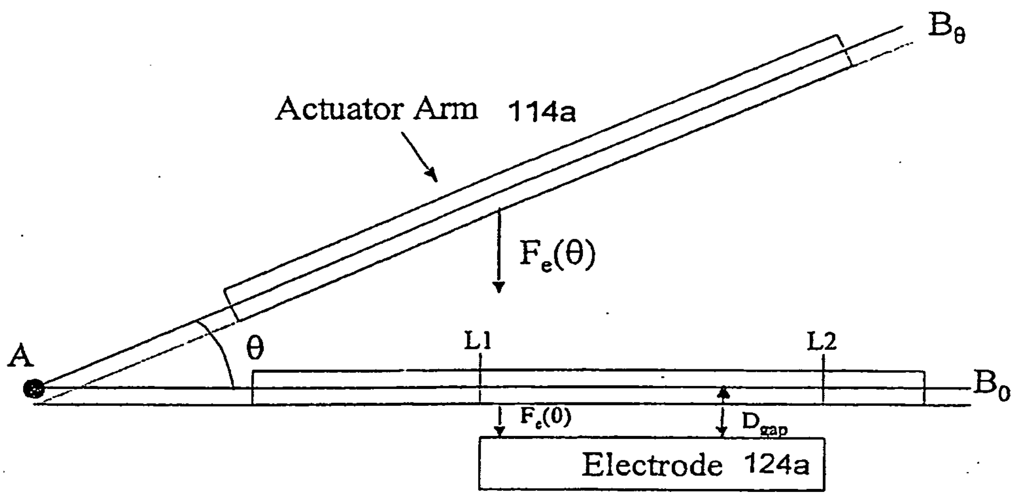

B$_\theta$
Actuator Arm 114a
F$_e$(θ)
A
θ
L1
L2
B$_0$
F$_e$(0)
D$_{gap}$
Electrode 124a

FIG. 5

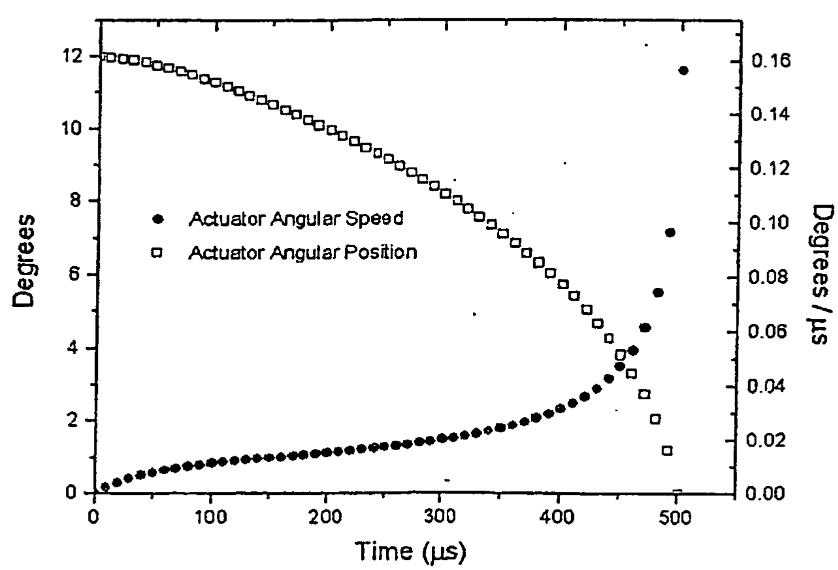

Actuator Angular Speed
Actuator Angular Position
Degrees
Degrees / µs
Time (µs)
0
2
4
6
8
10
12
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
100
200
300
400
500

FIG. 6

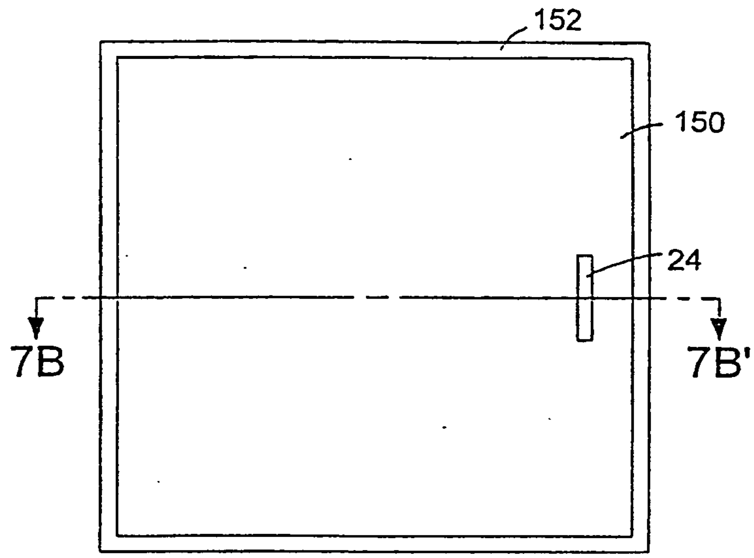


FIG. 7A

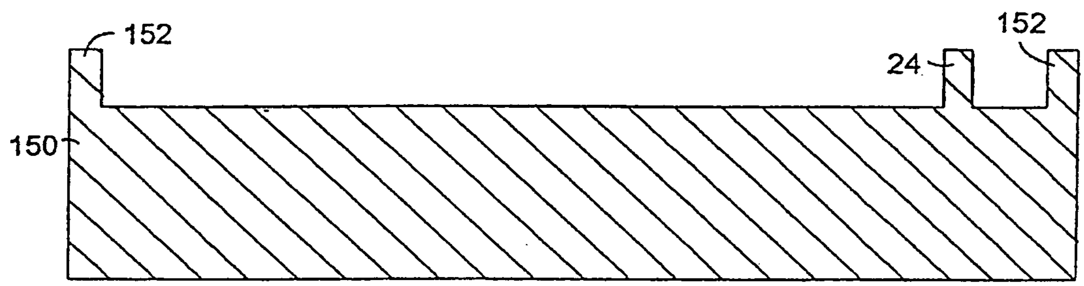


FIG. 7B

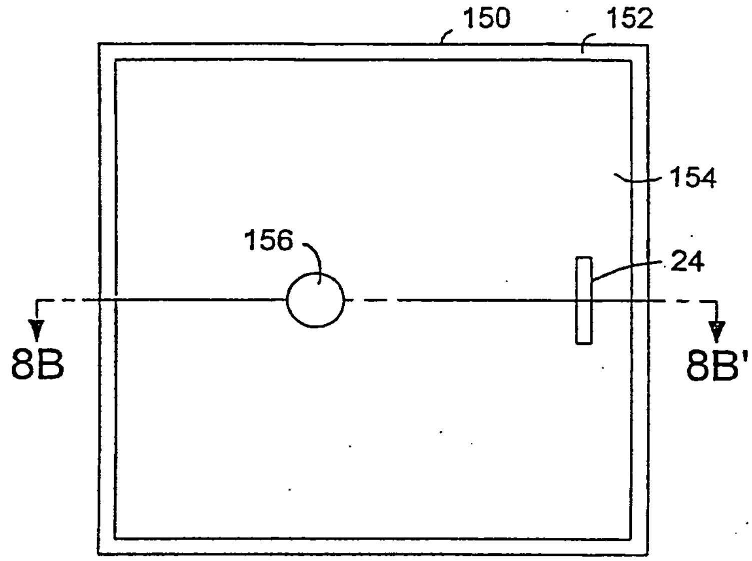


FIG. 8A

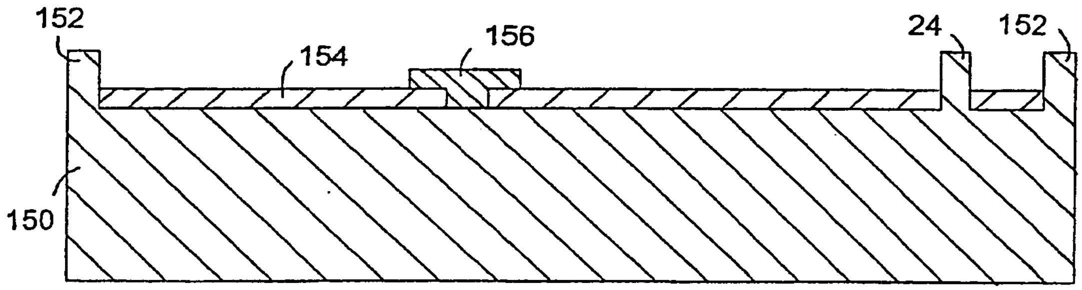


FIG. 8B

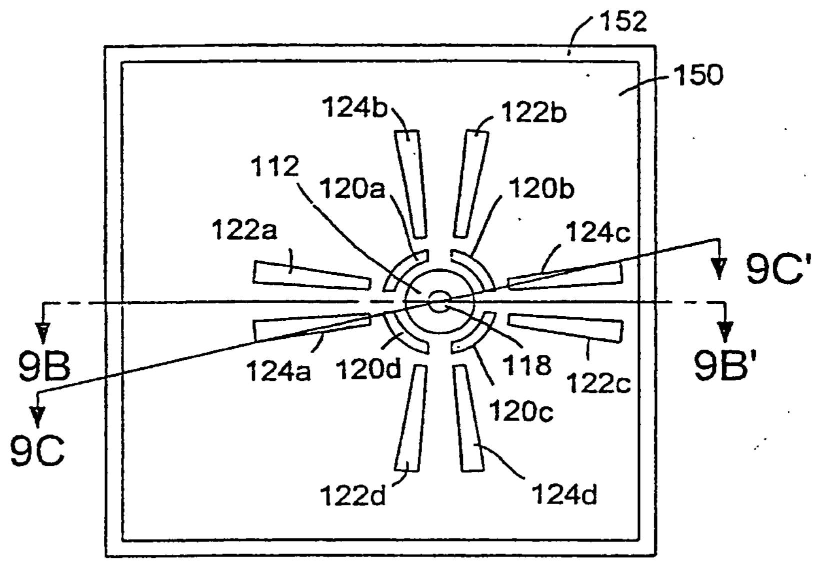


FIG. 9A

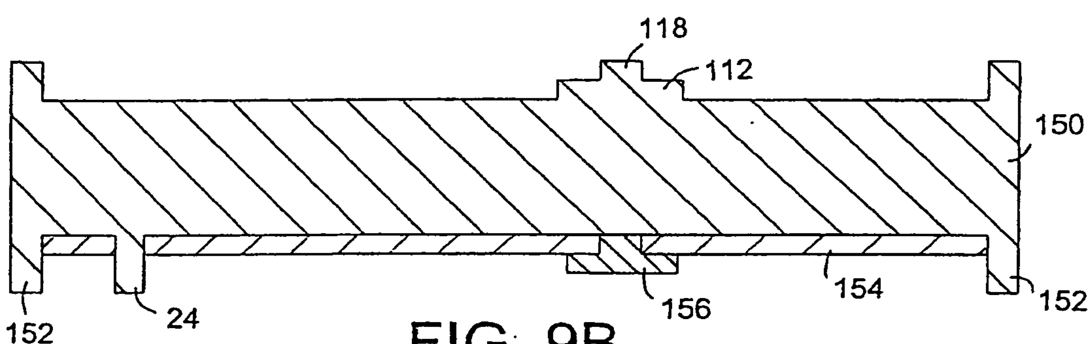


FIG. 9B

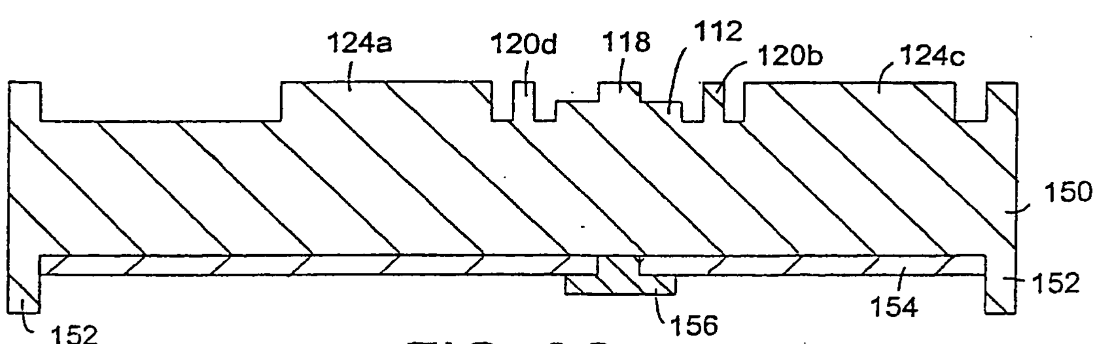


FIG. 9C

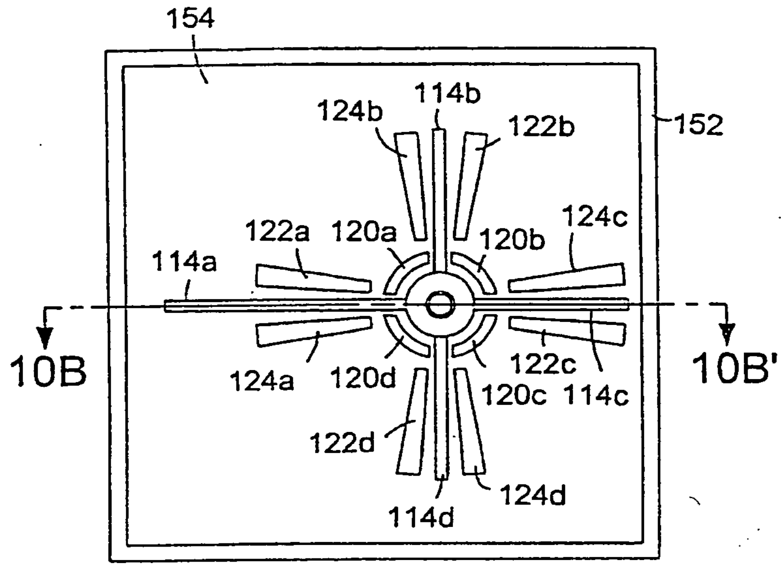


FIG. 10A

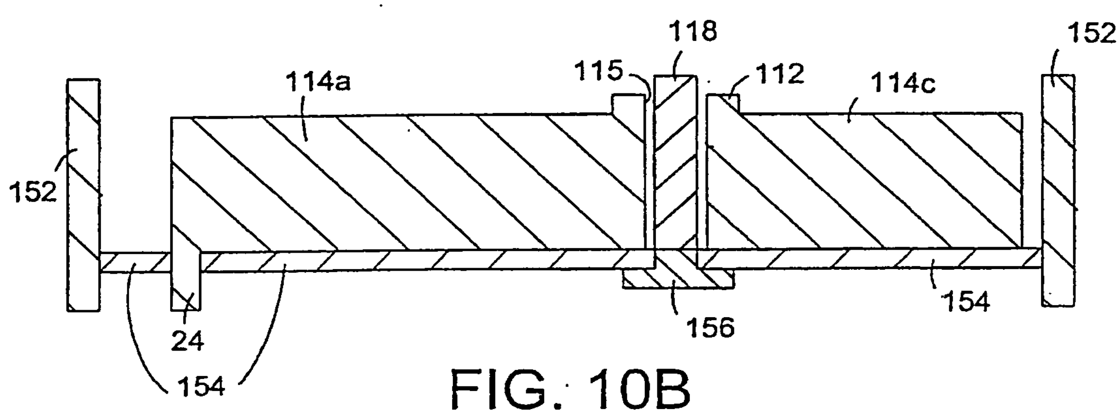


FIG. 10B

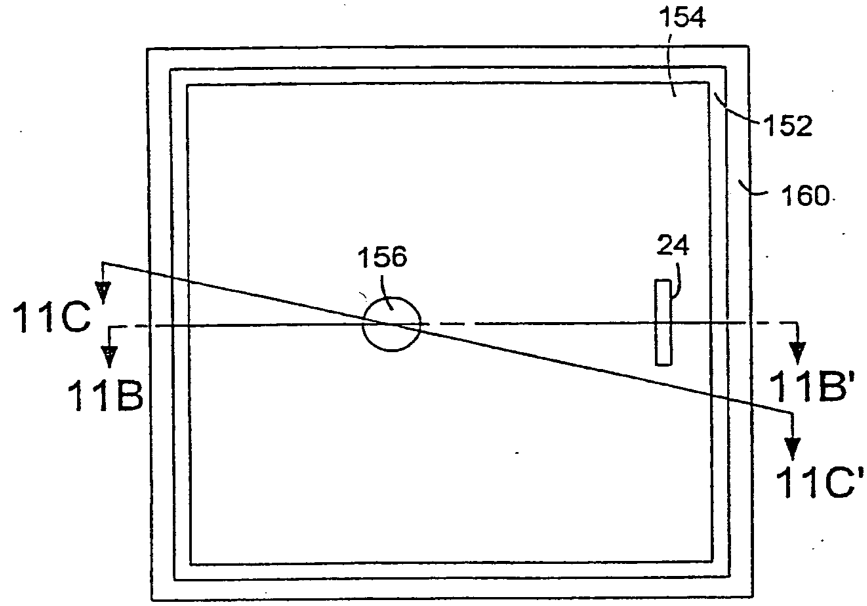


FIG. 11A

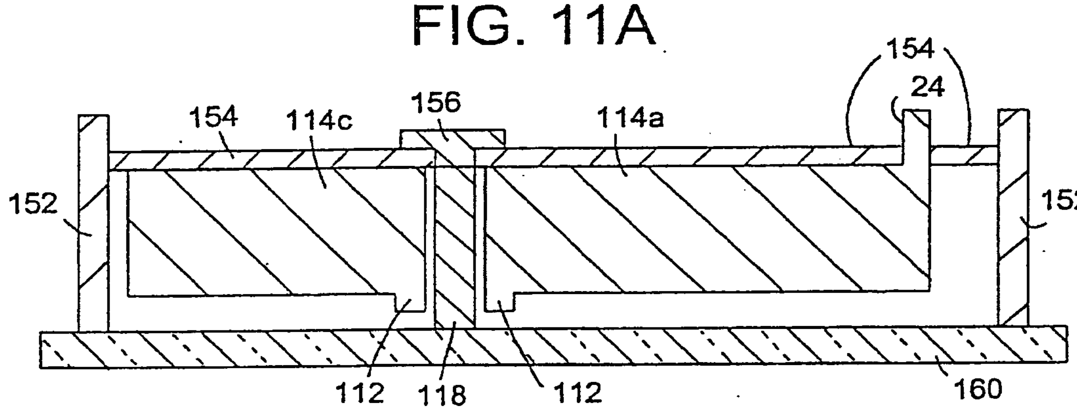


FIG. 11B

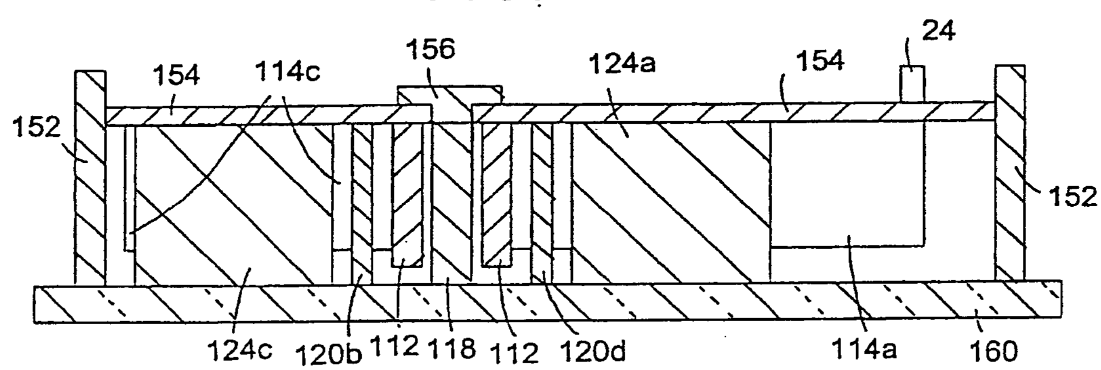


FIG. 11C

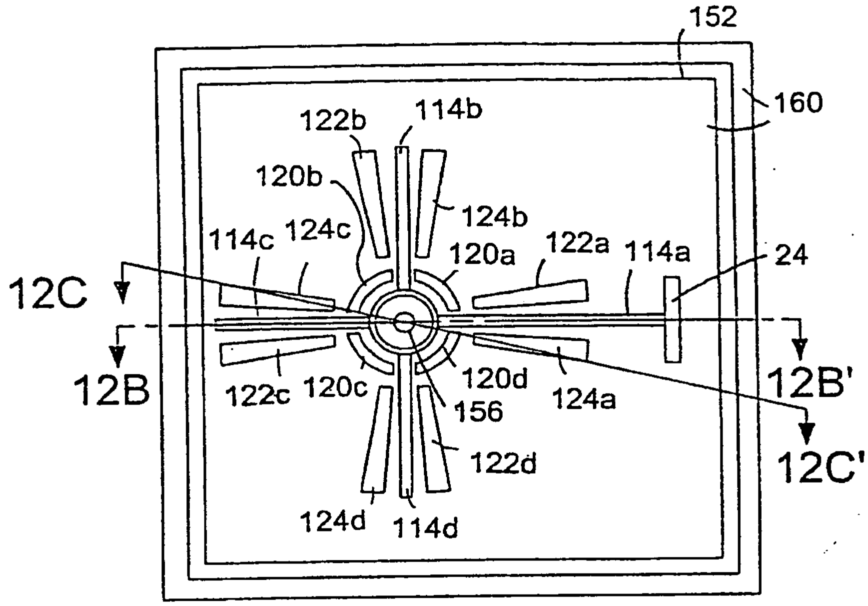


FIG. 12A

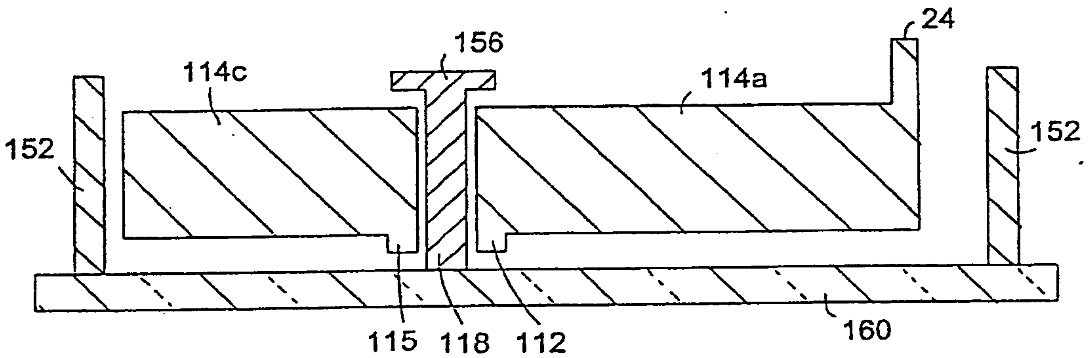


FIG. 12B

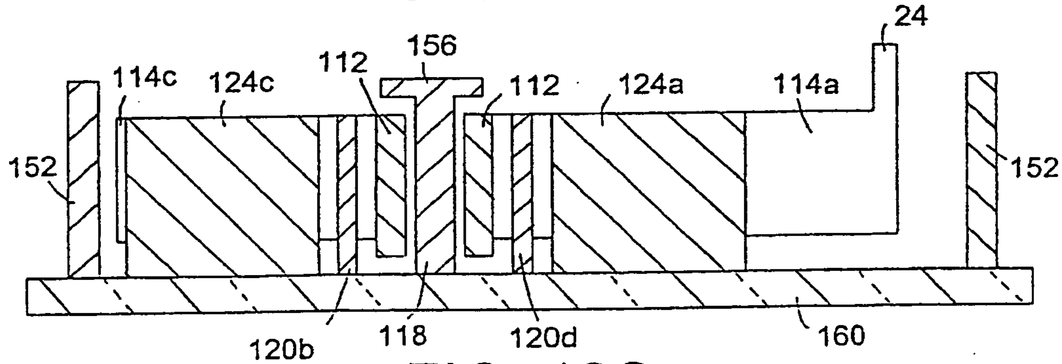
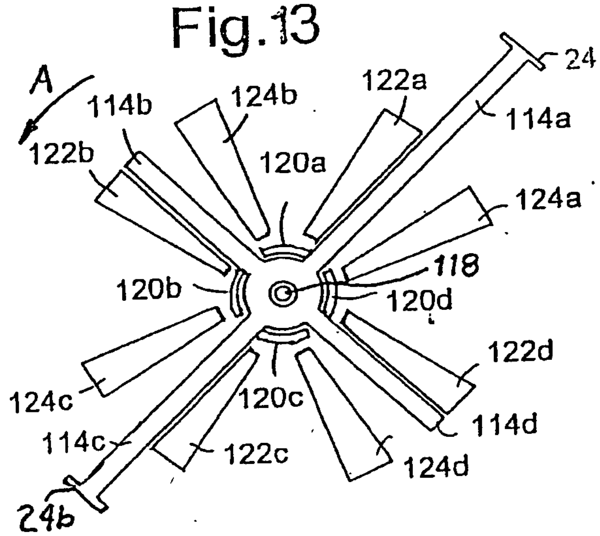


FIG. 12C

Fig.13


24
A
114b
124b
122a
114a
122b
120a
124a
118
120b
120d
122d
124c
120c
114d
114c
122c
124d
24b

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US01/07149

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : G02B 06/35
US CL : 385/18, 19

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 385/16, 17, 18, 19, 20, 21, 22, 23, 24, 47; 359/128

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
Please See Continuation Sheet

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	Toshiyoshi, H. et al. Electromagnetic Torsion Mirrors for Self-Aligned Fiber-Optic Crossconnectors by Silicon Micromachining. IEEE Journal of Selected Topics in Quantum Electronics. January/February 1999. Vol. 5, No. 1, pages 10-17, especially Figures 1 and 2.	1, 2, 7- 9
X	Toshiyoshi, H. et al. Electrostatic Micro Torsion Mirrors for an Optical Switch Matrix. Journal of Microelectromechanical Systems. December 1996. Vol. 5, No. 4, pages 231-237, especially Figure 2.	1-3, 9
A	Yasseen, A.A. et al. A Rotary Electrostatic Micromotor 1x8 Optical Switch. Micro Electro Mechanical Systems, 1998. January 1998. IEEE. Pages 116-120.	1-9
A, P	US 6,163,635 A (HELBLE) 19 December 2000 (19/12/00), see entire document.	1-9
A	DE 29618818 U1 (KRAUSE) 30 January 1997 (30/01/97), see enitre document.	1-9
A, P	US 6,094,293 A (YOKOYAMA ET AL) 25 July 2000 (27/07/00), see entire document.	1-9

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered .o involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search 16 May 2001 (16.05.2001)	Date of mailing of the international search report 01 JUN 2001
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703)305-3230	Authorized officer John D. Lee Telephone No. 703-308-0956

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US01/07149

Continuation of B. FIELDS SEARCHED Item 3: USPTO EAST, IEEE/IEL
search terms: MEMS, micromechanical, torsion mirror, switch, switches